MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MVLS-69-2

LIFE SUPPORT IN UNUSUAL ENVIRONMENTS

Principal Investigator : L. R. Young

February 1969

Second Semi-Annual Status Report on
NASA Grant NGR 22-009-312

MAN-VEHICLE LABORATORY
CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

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I. INTRODUCTION

The scope of this Life Support project calls for investigations into promising areas of biotechnology, with projections for future fertile research approaches.

The first year has produced a summary of research needs in the area of radiation and magnetic field effects on the nervous system (Man-Vehicle Laboratory Report MVLS-69-1). We are also investigating problems in trace contaminant monitoring, extravehicular propulsion, water reclamation and regenerative atmospheric control systems. Our current status and goals in each area are outlined below.

II. MONITORING OF ATMOSPHERIC CONTAMINANTS

(Mrs. H. L. Galiana)

Most trace atmospheric contaminants in a closed atmosphere occur in very small concentration and are easily removed by either the lithium hydroxide or the activated charcoal scrubbers used. However, for long duration exposures to a closed environment, monitoring measures are believed necessary to verify the correct operation of the removal system and detect malfunctions as well as to provide data on the concentration changes for later correlation with physiological measures on the occupants. Such studies would help substantiate, under weightlessness, currently accepted maximum tolerable contaminant levels or suitably change them, as well as increase our knowledge of the nature and synergistic effects of contaminants on humans.

Among those methods available for trace gas monitoring, the greatest technical advances for spacecraft applications have been made in:

1. Gas Chromatography: This method is currently preferred because of its safety, availability and relatively good performance in both identifying trace contaminants and quantifying their relative concentrations (Beckman.) Unfortunately its operation time is limited by the volume of stored carrier gas, and it requires periodic manipulation of samples of cabin atmospheres, increasing the size and weight of the system.

2. Mass Spectrometry: Although an excellent instrument has been designed to monitor the major gaseous concentrations (Perkin-Elmer), it is not considered as suitable for the analysis of low concentration multi-component complex mixtures. As the number of contaminants increases, their identification becomes a problem in pattern recognition of complex energy spectra. This can be alleviated by the use of temperature controlled sorption beds in front of the spectrometer inlet, thereby reducing the complexity of the mixture being analyzed at any given time (Perkin-Elmer). The power penalties are greater than in (1.) but the size and weight of the system is decreased. Operation time would be a function of the state of the sorption beds.

3. Infrared Interference Spectrometry: This method is the most recently developed of the three. It has the advantage of being capable of making continuous, automatic, passive measurements on the test atmosphere, with the required ppm or ppb sensitivity (Perkin-Elmer, Block Engineering). Although at the

moment, power penalties appear greater than in (2), further improvements should make this method the safest, and most reliable of all. Even now the size and weight penalties are less than in mass spectrometry and it has an indefinite operation time.

It has also been recently suggested by Tolliver et. al. (Aerospace Medicine, Vol. 40(1), pp. 35-39, 1969) that color changes in liquid crystals can be a measure of nearby trace contaminant concentrations. These ana other methods will be further investigated and compared.

The biological trace contaminants in a spacecraft present another problem. Any monitoring technique should preferably both differentiate between specimens and determine their concentrations, automatically. Unfortunately, in spite of the great variety of possible biological monitoring techniques, none of the currently available methods satisfies the required performance criteria; that is, to distinguish both between species of organisms and between viable and nonviable cells rapidly and automatically. Some of the techniques currently studied are:

1. Adenosine Triphosphate (ATP) or Flavine Mononucleotide - Luciferase Bioluminescent Assays:

The light produced in the reaction is a measure of the total ATP (or FMN) present in the sample, and therefore of the total viable microbiological contaminant concentration. The method is very sensitive (detect presence of 10-100 bacteria) but cannot differentiate between species. Automation is possible (Du Pont, Marquardt Corporation, Hazelton Laboratory) but the expected short storage lifetime of the luciferase is a problem.

2. Antibodies:

Antibodies against specifiec strains of microorganisms, viruses, and toxins are prepared prior to flight. The organism is detected by the presence of the corresponding microorganism-antibody complex. The method is thus rapid, sensitive and extremely specific but does not differentiate between viable and nonviable cells. Also it requires an apriori decision on which organisms to monitor and there is a problem of limited lifetime for the antibody preparations.

3. Gas Chromatography:

Still in the development stage, gas chromatography should be capable of identifying species of organisms (bacteria and viruses) by their characteristic spectrum of cellular organic molecules. Unfortunately the resolution appears very low (r 1.5×10^4 bacteria) and it is not yet capable of analyzing mixtures. Further work is warranted as it offers promise of identifying both microorganisms and viruses and of measuring their concentrations.

These and other methods will be further investigated. It is expected that by the end of summer 1969 a report on chemical, biological and aerosol contaminant monitoring techniques will be available.

III. ATMOSPHERIC CONTROL

(Prof. R. C. Reid)

Prof. R. C. Reid is investigating many phases of atmospheric supply and control in portable and cabin life support systems. There follows a brief outline of the current work status and visits made to various companies and plans for the next few months:

Visits

Mr. Aaron Schaeffer
Airesearch Manufacturing Company
Los Angeles, California

Visit December 6, 1968 to discuss their present, past, and future work in life support systems. A trip report was submitted which details the discussion.

Mr. G. L. Drake
Kearny Mesa Plant
General Dynamics Corporation
San Diego, California

Visit December 4, 1968 to discuss General Dynamics work in life support. A trip report was submitted.

61st Annual AIChE Meeting
Los Angeles, California
December 1-5, 1968

A paper was presented on life support in EVA and is included in Appendix A. Discussion with many other authors interested in life support work. Trip report submitted.

Hamilton-Standard
Windsor Locks, Connecticut
December, 1968.

Trip report submitted

Planned Visits

March, 1969

Houston Manned Flight Center
New Orleans AIChE Meeting - Symposium on Adsorption

May, 1969

Aeromed Laboratory
Wright-Patterson AFB

The literature survey is essentially completed. An excellent collection of reports dealing with all phases of atmospheric control in life support work is now available. We are beginning to write rough drafts for brochure. The sections to be rough drafted by June are:

Gas Storage Techniques
Carbon Dioxide Removal (Regenerator)
Carbon Dioxide Removal in EVA LSS
Oxygen Recovery from Carbon Dioxide
Electrolysis of Water
Trace Contaminants

It is also planned to organize a working conference on this phase of the project in the fall of 1969.

IV. WATER RECLAMATION

(John Tole)

Investigations into water reclamation and monitoring techniques were begun a few months ago. An outline of the study in progress is included.

The selection of a water recovery system for future spacecraft is complex due to the uncertainties of mission length, crew size and process development among others. In connection with the selection process, the Man-Vehicle Laboratory is preparing a study of water recovery systems with the intention of enumerating the most promising process methods which are or may become available, the choices from among those methods which may be best for a specific mission, and the various problems in this area which require research.

The processes which appear to hold the most promise for water recovery are: Air Evaporation, Vapor Diffusion, Forced Cirulation/Flash Evaporation and Micro Filtration, the latter being unsuitable for recovery from urine. Several other processes might be acceptable with suitable development and will be discussed in the final report.

The Russians and others have also investigated water recovery as a portion of a closed ecological system. A myriad of problems are inherent in the fully closed approach, but for long duration missions it may have some advantages if fully developed. Another novel proposal has been to store both food and water in the form of fuel for an ion thruster, waste products and any excess fuel being channelled directly to the thruster. This concept also entails a number of problems but might warrant further consideration.

Once certain processes have been deemed suitable for spacecraft water recovery, some type of selection and optimization procedure is required. There are a number of variations to this approach. One technique is to assume three or four configurations of a specific process or combination of processes and attempt to optimize each scheme by iterative methods. Any selection procedure must deal with the problem of reliability in some manner. Several studies have shown that a repair-replace philosophy is superior to a parallel-redundancy scheme in improving reliability. Computer simulations of water systems with random failure analysis have been performed by several groups.

Another important consideration is the potability of the product water from these systems. Currently, potability is assumed or inferred from conductivity tests of the processed water. It is felt by some that an on line monitor would be a considerable improvement not only in this application, but also for use in municipal water systems. A number of rapid tests of potability have been and are being developed notably the bioluminescense assay. To assume water is sterile for long periods of time seems dangerous, but to involve astronauts in time consuming water analysis to any great extent is not wise either. On-line automatic potability monitoring and refinement of standards would appear to be an important goal for the future.

Once the water has been made potable, it must be kept sterile. The most successful method to date has been simple pasturization at 160°F. There is some question as to whether one hundred per cent sterilization is advisable. Some pathogenic organisms may thrive in an environment free of their natural enemy organisms. Some type of automatic sterilization procedure is advised in the event of contamination during a mission.

A number of fringe topics are in need of study. One is how various water reclamation components and processes operate in a weightless environment. This would be of value in developing optimum systems. Another is the reaction of the water recovery and other life support systems to radical changes in crew activity. In this connection, some researchers have pointed to the need for a simple method of monitoring body mass accurately in order to determine day to day water balance.

Lunar and planetary based stations should not be neglected when considering recovery equipment. The requirements for a stationary semi-permanent, gravity influenced installation may be quite different than those for a spacecraft.

The subjects above and several others will be covered in detail in the final brochure which should be available in a few months.

V. EXTRAVEHICULAR PROPULSION

(L. C. Von Renner)

A research assistant has been investigating present propulsion techniques for EVA. A resume of his work and goals follows.

Research during the last few months in Extra-Vehicular Activity centered around two activities:

1. a survey of the several propulsion and attitude control devices currently under study by NASA or private industry, and

2. a feasibility study of an attitude control system based on the involuntary muscle contractions of the ankle used to maintain balance.

These two activities are described separately.

A research survey is being conducted to determine the state-of-the-art of several kinds of propulsion schemes. The purpose is to determine the current themes of research, the existing limitations and the frontiers of knowledge, and the relative utility of several EVA control, stabilization and propulsion techniques. The goal of this study is a wide-ranging statement of promising objectives for future research. "Promising" is defined by three criteria: 1. applicability to future EVA missions, as they are anticipated; 2. need for additional research to qualify as feasible; 3. suitability for laboratory investigation and, particularly, for graduate research topics. This exercise in research planning will emphasize the so-called "unstabilized" or open loop attitude control scheme wherein the astronaut must consciously initiate corrections to his attitude. This emphasis exists because 1) the "stabilized" system has received much attention and is represented by the advanced LTV version called Astronaut Maneuvering Unit (AMU), and 2) a use exists in future EVA missions for an open loop system requiring less hardware and boasting increased reliability.

As a specific project, the development and application of a postural reflex model to the EVA mission was considered. The postural reflex model represents an, as yet, unidentified theory of man's involuntary ankle muscle movements which are employed to maintain normal balance. Such movements in space, occurring naturally in response to drifting attitude, could be recorded, converted to electric signals, and used to activate effectors which would restore correct orientation. For example, Grumman Aircraft, in their Manned System Dynamics Division, investigated the use of the human balancing reflex to balance and control a hydraulically driven carriage capable of short horizontal excursions. Information extracted from experiments at NASA/LANGLEY and in our own lab, largely discredited the theory that similar ankle responses would be registered in a zero-G environment where proprioceptive inputs are largely absent. Research is shifting, therefore, from the use of involuntary to voluntary muscle control. Every voluntary muscle contraction is accompanied by a measurable electric signal, an electromyogram (EMG), which may be processed and used to activate effectors. Thus, an application of the EMG similar to that used to develop the Boston (prosthetic) Arm may prove feasible for EVA.

During the next quarter, results from the EVA survey will be condensed and organized into a list of promising research topics. Experiments will also begin in the use of the myo-electric response and voluntary movement as control signals for attitude control.

APPENDIX A

PORTABLE LIFE SUPPORT SYSTEMS FOR EXTRA-VEHICULAR ACTIVITIES

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Presented at the
Symposium on Aerospace Life Support Systems, Part 1
Sixty-First Annual AIChE Meeting
Los Angeles, California
December 1-5, 1968

PORTABLE LIFE SUPPORT SYSTEMS
FOR EXTRA-VEHICULAR ACTIVITIES

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Cambridge, Massachusetts

It is by no means an easy task to design a reliable, light weight portable life support system to keep a man alive and comfortable outside the environs of his space capsule. First, he (or she) must be protected against the vacuum of space by some form of pressure suit; micrometeorite shielding is necessary; absorption of solar radiation must be minimized; and work capacity must be provided with arms or external manipulators. It is not, however, the purpose of this paper to discuss suit design. The suit requirements noted above usually result in what one might call an adiabatic environment for the astronaut. There is little thermal exchange with the environment by radiative heat transfer and obviously no interaction by convective or conductive heat transfer. Thus, almost all of the metabolic energy must be dissipated by special techniques. The astronaut must be provided with sufficient oxygen with no appreciable accumulation of carbon dioxide or other trace contaminants such as body odors. For short term missions (a few hours), food and water supplies are not necessary nor is waste disposal a problem though it may be necessary to provide storage for urine or even feces.

Most portable life support system problems center around the areas of optimizing the oxygen supply, the removal of carbon dioxide and trace contaminants, and the dissipation of metabolic energy. The problems are typical of those encountered in chemical engineering. Before discussing any detailed engineering ideas, however, it is necessary to establish some ground rules which seem reasonable for astronaut missions in the near future.

Ground Rules Based on Physiological Experiments

To live, man consumes oxygen and liberates principally carbon dioxide, water, and energy. The metabolic rate of energy release is closely related to the oxygen consumption rate and the carbon dioxide liberation rate. For example, as shown in Figure 1, a normal person sitting quietly (with no nervous stress) liberates some 300 Btu/hr of heat energy and consumes about 0.05 lbs of oxygen/hr. The carbon dioxide liberation rate is dependent upon the individual; the rate is related to the respiratory coefficient, (RQ), i.e., the atoms of CO_2 liberated per atom of oxygen used. If this ratio were unity, then 1.37 lbs of CO_2 would be formed per lb of oxygen consumed. Normally, the RQ is about 0.82, i.e., 1.1 lbs CO_2 are formed per lb O_2 used.

Figure 1 shows a wide range in metabolic loads and, for orientation purposes, some work and play activities are also noted. Maximum astronaut metabolic loads were originally estimated to be in the range of 1000-to-1600 Btu/hr. Experience has shown (though the reasons are not necessarily clear) that astronauts experience much higher metabolic loads, near 2000 Btu/hr, and, in some circumstances, even much higher. Thus, on Figure 1, following the recent NASA criteria, the normal load is set at 2000 Btu/hr with maximum short term loads to 4000 Btu/hr. Normal oxygen consumption is about 0.375 lb/hr and the CO_2 production (RQ = 0.82) 0.41 lb/hr. These figures are in accord with current NASA specifications.

The pressure in the space suit should be as low as possible to reduce leakage and to increase the flexibility of the present suits. However, the partial pressure of oxygen should not be significantly less than the 160 mm Hg (3.1 psi) required at sea level. If a two-gas atmosphere were used, higher total pressures are required with the concomitant disadvantages of higher leak rates, more rigid suits, and the necessity of monitoring the fraction oxygen. However, some medical opinion has been expressed that pure oxygen atmospheres are inherently dangerous and after a period of a few weeks there appears to be a tendency of the lung sacs to stick together with a loss in ventilation capacity (12). This problem should not arise for a short term EVA*, so a pure, low-pressure oxygen atmosphere is a realistic choice.

The carbon dioxide level must be maintained low; how low is still a question. Present specifications limit the CO_2 partial

* EVA is the standard short-hand notation for extra-vehicular activity.

pressure to about 10 mm Hg though there is some evidence that 20 mm Hg may be tolerated for short periods. In any case, concentrations much above 10 mm Hg may result in headaches and confused mental activity. High concentrations lead to unconsciousness. The available data indicating the desirable and undesirable oxygen and carbon dioxide levels are summarized in Figures 2a and 2b (4).

Trace contaminants are very difficult to define, measure, or to delineate any limits. Ordinarily, the more undesirable types are compounds containing sulfur or nitrogen. Present specifications simply state that such materials should be "removed".

The final physiological areas requiring comment are temperature and humidity. Entire books have been written on this subject and many detailed experiments made. Suffice it to say here that a) a definite metabolic energy output must be removed, b) the humidity should not be such as to fog the helmet visor or to cause discomfort, and c), the skin temperature over most of the body should be kept sufficiently low in order to minimize "active" sweating. Tests indicate that men feel more comfortable and are more alert if the body skin is relatively cool. This has led to the development of liquid-cooled undergarments in which interwoven small hollow plastic tubes in the garment are in contact with the skin. Coolant circulated through the tubes effectively removes excessive metabolic heat and maintains the skin cool and non-sweating. In addition, some gas circulation is required over the cool skin areas to remove insensible perspiration, the latter resulting from evaporation of the water that diffuses through the skin. Such insensible perspiration is usually not large and does not contribute a large fraction to the total metabolic load. For astronauts with a metabolic activity equivalent to 2000 Btu/hr, some 1600 Btu/hr would be removed by the cool liquid circulating through the undergarment tubes and 400 Btu/hr from insensible perspiration and respiration.

In summary, an astronaut normally must be provided with about 0.38 lbs/hr of oxygen and means for removal of 0.41 lbs CO_2/hr, trace contaminant gases, and 2000 Btu/hr metabolic energy. Equivalent mission times, including short term high metabolic loads and a safety factor, usually run to about 7 hours. In 7 hours, 2.63 lbs O_2 are needed, 2.87 lbs CO_2 are to be removed, and 14,000 Btu dissipated. To accomplish these objectives, many schemes have been proposed and these are discussed below. Only techniques suitable for portable systems are considered here. Some very promising techniques applicable to the spacecraft environmental system or to long term missions are specifically excluded (26).

Oxygen Supply

It would certainly be simplest to supply the oxygen from the spacecraft via the umbilical cord. This, in fact, was accomplished in the first EVA tests (13) with excess oxygen and metabolic CO_2 vented. The desire to have a self-contained life support system eliminates this choice, though it still may have some utility in special situations.

Next in line of simplicity is high pressure gas storage. Optimum pressures from a weight and volume analysis indicate that charging pressures in the range of 3,000 to 7,500 psia should be used (14)* Present oxygen storage systems on the spacecraft use supercritical, cold gas at about 800 psia. To compress this gas to 3,000-7,500 psia for recharging astronaut supply cylinders is not convenient nor are the energy requirements negligible (23). Schemes to recharge with liquid or solid oxygen (the latter to be moved by magnetic fields) and pressurization by evaporation are possible but introduce new problems. These considerations have prompted many people to propose alternate oxygen sources. Such sources involve the decomposition of a chemical to produce oxygen as a product, or involve the reaction of a chemical with metabolic water and carbon dioxide to produce oxygen.

Examples of the first type can easily be found though only a few are noteworthy when stability, safety, weight, and undesirable by-products are considered. For example, perchlorates have been studied extensively (20), and one prototype system using this chemical as an oxygen source is being constructed. High decomposi-

* A suggestion has been made to expand the high pressure stored oxygen down to helmet pressure and utilize this work to replace the batteries. This is not likely to occur. At the oxygen flow rates discussed previously (0.375 lbs/hr), expansion in an isothermal, reversible turbine at 500°R from 3000 to 3 psia will only produce 24 watts and provide a net refrigeration of 81 Btu/hr. Any real expansion would obviously be less efficient.

tion temperatures are required and unless great care is taken, chlorine is liberated in small amounts. Nitrogen chemicals such as NH_4NO_3 and the nitrogen oxides have been studied and rejected for many reasons (22) though another proposal for the use of nitrous oxide has recently been made (1). The most promising chemicals appear to be sodium chlorate and hydrogen peroxide (28). Multiple chlorate candles are envisioned, but there are some problems in preventing preignition or partial decomposition prior to actual ignition. Concentrated hydrogen peroxide can be easily decomposed over a silver catalyst and the oxygen separated from the water in a porous Teflon pad (29). The residual water is available for later use in a heat exchange system for dissipating excess metabolic heat.

All of these chemical techniques involve exothermic reactions and the chemical energy release must be dissipated along with metabolic heat. These energies are not small. For instance, to decompose sufficient 90% H_2O_2 at a rate to produce 0.38 lbs O_2/hr, the reaction liberates about 1000 Btu/hr, which is about 50% of the total astronaut metabolic heat load.

The second type of chemical oxygen generation utilizes peroxides or superoxides of the alkali metals. These react with CO_2 and water to produce the carbonate-bicarbonate salt with oxygen evolution. Li_2O_2 looks attractive from a weight standpoint (20) but experiments have shown that oxygen is held in the Li_2CO_3-$LiHCO_3$ mixtures as rather stable H_2O_2. LiO_2 has not yet been synthesized and is believed unstable (29). Oxygen may also be produced in the reaction between potassium superoxide (KO_2), carbon dioxide, and water to produce a carbonate-bicarbonate salt and oxygen gas (16, 17, 19)*. In recent work, $CuOCl_2$ has been added as a catalyst to enhance the rate. With sufficient consideration given to the mass transfer characteristics of a KO_2 bed, it appears that this technique will remove metabolic CO_2 and produce most, if not all, the required oxygen. Some metabolic water will also be removed. Probably this technique (or one using sodium superoxide) is more suitable for the spacecraft rather than a portable backpack due to the bulk and the possibility of either dusting or packing-channeling if the bed is jarred. Also, as noted earlier, the reaction is exothermic and it is desirable to reduce the heat load for a backpack as much as possible. KO_2 is hazardous and may cause ignition if in contact with organic materials and, since O_2 liberation is coupled to CO_2 production, a suit leak will result in a drop in total pressure. In the latter case, auxiliary oxygen storage is mandatory, thus a KO_2 or NaO_2 system must be used with a back-up oxygen supply system.

In summary, though many techniques have been suggested, oxygen storage as a high-pressure warm gas, supercritical cold gas, liquid, or even solid appears to be most feasible. Other possible techniques which are under active consideration are multiple sodium chlorate

* It has been suggested that the Soviet Vostok spacecraft used chemical regeneration with superoxides to provide oxygen (25).

candles, high concentration hydrogen peroxide, and potassium or sodium superoxide, the latter also functioning as a carbon dioxide absorber.

Carbon Dioxide Removal

The present method of removing CO_2 is to absorb it in a moist, solid LiOH bed. The method is simple and reliable. These facts have not deterred many investigators from suggesting alternate methods, some of which may be very promising. The KO_2, NaO_2 reaction has been mentioned above. Another means which shows real promise is membrane permeation (24, 30, 31, 34). The best membrane found to date is a liquid membrane of either Dacron or cellulose acetate impregnated with a $CsHCO_3$-Cs_2CO_3 solution with a sodium arsenite ($NaAsO_2$) catalyst. A membrane made from a 2.6 mil film impregnated with a 6.4 N $CsHCO_3$, 0.5 N $NaAsO_2$ showed a CO_2/O_2 separation factor of 4100 and a CO_2 permeability of 214 x 10^{-9}* These values may be compared with the best polymeric CO_2/O_2 permeation membrane which has a CO_2/O_2 separation factor of 5.5 and a CO_2 permeability of 300 x 10^{-9}. (Pure water has values of 22 and 210 x 10^{-9}).

In the liquid membrane, the HCO_3^- diffuses across the film as indicated by the gradients shown in Figure 3. The CO_2 flux was chemically rate-limited and the sodium arsenite was added as a catalyst. CO_2 may be recovered on the downstream side of the membrane, though in EVA work, this would not normally be done.

* Permeabilities are expressed as $\frac{\text{cc gas NTP-cm}}{\text{sec-cm}^2\text{-cmHg}}$

In practical application, thin silicone rubber membranes are used to sandwich the liquid membrane and a polyethylene screen is employed as a strength member.

Most other carbon dioxide removal schemes employ some sort of adsorbent or absorbent wherein physical or loose chemical bonds are formed. The most common adsorbents are molecular sieves (8, 15, 33). High CO_2 loadings can be attained and desorption may be accomplished without high temperatures if a good vacuum sink is employed. A single molecular sieve bed is far too large for a backpack though dual beds may be used. The weight and volume of a dual bed system is reasonable if a short cycle time is employed but the necessity of providing valves and a switching arrangement leads to a loss in reliability. Also, as is well known, water is strongly adsorbed on molecular sieves and is difficult to remove without heating and purging. Most molecular sieve schemes use a silica gel pre-drier which adds more weight and introduces the problem of drying the silica. Also, dusting may be a problem though this can be eliminated by appropriate filters. Oxygen losses during desorption are small. Adiabatic adsorption and desorption involves large energy effects and many designs have incorporated cooler-heater inserts to prevent large temperature swings.

Another regenerable CO_2 adsorbent is charcoal (32). It has some advantages over molecular sieves since water is cosorbed and easily desorbed without affecting appreciably the equilibrium CO_2 loading. On the other hand, oxygen is also cosorbed and subsequently lost in desorption.

Another CO_2 removal system under active study involves the use of Li_2O rather than LiOH. Lower weights are possible but, until recently, internal mass transfer rates in the granules were very low (2). New methods of preparation have greatly improved this rate process (6). There is some question about the efficiency of Li_2O beds in a low humidity gas. Apparently the partial pressure ratio of H_2O/CO_2 should be 1.5 to 2.0. This ratio is considerably larger than the NASA specifications that call for a maximum each of 10 mm Hg H_2O and CO_2 in the helmet atmosphere though the ratio in normal exhaled breath is about 2.4. Apparently prehydration of Li_2O to LiOH is necessary to activate the bed.

Other techniques involve the reversible absorption and reaction of CO_2 with organic amines or silver oxide (8, 9, 23) magnesium, barium, and calcium oxides (in hydroxides) (15, 23) or freeze-out on a cold surface (5). While all these methods are feasible under certain conditions, they do not appear to yield any real advantages in a backpack design for EVA.

In summary, LiOH beds are currently in use and reasonably satisfactory. About 0.8 lbs of CO_2 may be removed per pound of LiOH (about 90% of theoretical). The beds are not regenerative and are quite bulky. The most promising improvements involve the liquid membrane or the substitution of Li_2O for LiOH.

Contaminant Removal

In short term EVA missions, charcoal traps seem to work effectively for contaminant removal. For longer range missions involving many men, catalytic combustion or radiation decomposition of the impurities may be more conservative in weight and volume requirements.

Humidity Control and Energy Dissipation

Humidity control is discussed with energy dissipation concepts since most humidity control systems utilize gas cooling with subsequent condensation and separation of the excess moisture.* All discussions in this general area lead to the present proposed Apollo concept developed by Hamilton-Standard and shown in Figure 4 (3, 11, 18, 21). The body torso is watercooled via small tubes woven into the undergarment. A circulating gas system provides cool, dry oxygen to the helmet from which it circulates over the body to remove insensible perspiration. CO_2 is removed in a LiOH bed and oxygen is supplied from a pressurized gas source. An emergency oxygen sphere is also provided to allow for a system malfunction and to provide time for the astronaut to re-enter the spacecraft -- the metabolic heat is stored during this short time period. Short term storage is possible since for a 150 lb man ($C_p = 0.83$), 600 Btu may be stored before the "deep-body" temperature rise exceeds the allowed maximum of 4.6°F (7).

* Permselective membranes are also being studied to vent the respiratory and insensible perspiration water to space. Cellulose aceate membranes may be applicable, but quite promising results have also been obtained with porous Vycor glass. The pores in the glass must initially be filled with water. After this, providing the pores do not dry out, there is an excellent separation of water from the carrier oxygen.

Liquid suits were chosen since gas circulation cooling is insufficient to remove the projected 2000 Btu/hr (7). A schematic of the LiOH-charcoal canister is shown in Figure 5. The humidity control and heat dissipation unit is the key to the system. Both circulating oxygen and warm water from the suit flow through cored passages in a porous metal plate sublimator. Stored water is fed to this sublimator and is in contact with porous surfaces facing space. As water passes through the porous plate, it evaporates and eventually freezes, thus cooling the unit. Under low heat loads, the ice layer on the vacuum side prevents further water loss; as the heat load rises, the ice warms and evaporates. The unit is said to be self-regulatory. A cut-away view of the unit is shown in Figure 6. As the humid air cools, water condenses the drops are "thrown-out" by centrifugal forces, caught on a wick and carried by capillary forces to one end of a feedwater reservoir shown in Figure 7. Some oxygen is also carried to this reservoir. The separated water and oxygen compress a bladder in the feedwater reservoir and thereby force the stored water into the subliming sections of the porous plate cooling unit.

The entire loop is very cleverly conceived and well designed. It is the primary unit planned for the Apollo EVA series. The unit, not including the water-cooled suit, is not light. An early design for 4 hours, at a low heat load (5550 Btu total) weighed over 50 lbs with a volume of about 2.2 ft^3. Units compatible with the more recent NASA requirements (7 hours, 14,000 Btu total) are expected to be larger and heavier.

This over-all system bears out the intrinsic feeling that life support systems, when designed and built, are bulky, complex, heavy units. Any real improvements in weight and volume must come in the thermal control system. To arrive at general conclusions, it is first necessary to examine critically some methods which have been proposed to date. The Hamilton-Standard porous-plate sublimator has already been discussed, however, the general concept of expendable refrigerant systems can be analyzed in a rather simple way.

Expendable Refrigerant Systems

An expendable is, of course, a material which is eventually rejected to space during the cooling operation. With this simple concept, one can immediately arrive at certain very general conclusions which are independent of many of the actual details of the cooling mechanism. Consider the cooling device as a conceptual box as shown in Figure 8. Initially it is charged with a mass M_i of an expendable material and at any time during the operation there is a mass M present. During operation, it accepts a heat-energy flow of $\dot{Q}$; this term has units of energy/time and is not constrained to be constant. Also, during operation, there is a flow of material to space. Designating this flow rate as $\dot{M}_o$ and noting that associated with this flow there is an enthalpy, h_o, then one can immediately apply a transient first-law balance to give:

$$\frac{d}{dt} \quad (EM) = \dot{Q} - \dot{M}_o \quad h_o \qquad (1)$$

E is the specific internal energy of the material in the box at time t. Expressing $\dot{Q}$ as dQ/dt and $\dot{M}_o$ as -dM/dt, then:

$$d \ (EM) = dQ + h_o \ dM \qquad (2)$$

$$Q = \int_t - (h_o - E) \ dM + \int_t \ MdE \qquad (3)$$

As dM < 0, then to maximize Q, it is obvious that h_o should be as large as possible and the residual fluid energy E should be as large as possible, relative to the initial energy of the fluid E_i.

As a simple illustration of Eq. (3), suppose that the original fluid were a liquid at some temperature T_i; cooling is accomplished by evaporation of this fluid at constant temperature T_i. Then dE = 0 and $(h_o - E)$ = latent heat of evaporation = constant = ΔH_v.*

Thus,

$$Q = \Delta H_v \ (M_i - M_t) \qquad (4)$$

where M_t is the mass at time t.

* The internal energy E and enthalpy h of a liquid are essentially identical.

Returning to Eq. (3), it is interesting to examine it in more detail. First, consider the enthalpy of the material leaving, h_o. It is obvious that the phase should be a gas. If this gas were a vapor in equilibrium with some condensed phase (liquid or solid), the enthalpy is well defined. Also, it is interesting to note that enthalpies of saturated vapors are usually not strong functions of the saturation temperature or pressure. For water, the saturated vapor enthalpy (relative to h = 0, saturated liquid, 32°F) is shown in Table 1 for several temperatures:

Table 1

Enthalpy of Saturated Water Vapor

T,°F	h, saturated vapor, Btu/lb
100	1105
60	1088
32	1076
-20	1053
-40	1044

Compared with the approximate 10^3 Btu/lb of a latent heat of evaporation, these changes are relatively minor. Still, when convenient, if saturated vapors are to be ejected, the higher the temperature, the larger the value of h_o.

Next, it is interesting to examine briefly whether the phase change process should be carried out as a liquid-vapor or solid-vapor transition. We make the assumption in both cases that the initial charging conditions are identical in the comparison and that h_o is a constant for both cases, though not necessarily the same in both. Eq. (2) is immediately integrated as:

$$(EM)_t - (EM)_i = Q + h_o \ (M_t - M_i) \qquad (5)$$

M_i, E_i, h_o are constants. To maximize Q, we wish to have E_t as large as possible for any time interval when $(M_i - M_t)$ has left the cooler. Certainly, the more favorable case is one in which the fluid is liquid rather than solid since E (liq) > E (solid). If one considers an overall process where the cooler is depleted of all expendable, $M_t = 0$ and

$$Q_{total} = (h_o - E_i) \ M_i \qquad (6)$$

In this case, it is easy to see that it makes no difference whether the transition is solid-to-vapor or liquid-to-vapor because the cooling capacity is dependent only upon the state of the fluid leaving, the initial charging conditions, and the initial mass.

In summary of these general ideas, one should maximize the exit fluid enthalpy and minimize the initial fluid energy and, if residual fluid remains, its energy should be maximized.

If the ejected fluid resulted from a phase transition (liquid-to-gas or solid-to-gas), it has already been noted that high phase transition temperatures are desirable since this increases the exit fluid enthalpy.

To increase this rejected-fluid enthalpy still further, several interesting schemes can be suggested. Certainly the rejected fluid could be used to precool circulating coolant from the suit. Low-pressure gas--liquid heat exchangers would then be necessary and the possible increase in rejected vapor enthalpy is small. Such a technique does not, at first sight, seem worthwhile.

Of more interest is a technique whereby the rejected fluid is expanded through a well-designed nozzle. The temperature drop in the expansion would encourage the nucleation and growth of a solid phase. Just prior to the recovery system, the solid phase would be separated and the final gas temperature would be higher than the original value. By various ways, the separated solid (ice--if water were used) could be made to sublime and thus remove additional heat from the system. This procedure certainly adds mechanical complexity and preliminary calculations indicate that to be truly effective a converging-diverging supersonic nozzle is necessary. The scheme needs careful engineering evaluation to assess its potential value. The one encouraging note is the fact that somewhat similar expansions and solid separations have apparently been carried out using CO_2.

It is clearly obvious that the lower the initial energy of the stored expendable fluid, the higher the net heat load per unit mass of such fluid. Suppose water were to be used and stored initially at 70°F, then E = 38 Btu/lb. However, if one could store water initially as ice, then depending on temperature, the respective values of E are given in Table 2.

Table 2

Internal Energy of Ice

T, °F	E (ice), Btu/lb
32	-143
-20	-168
-40	-17
-320	$\sim$ -310

Thus, taking the extreme case of T (ice) = -320°F, the energy sink between this solid state and liquid water at 70°F is (38 - [-310]) $\cong$ 350 Btu/lb. This value is about 33% of the latent heat of evaporation in the 50-70°F range. Of course, the undesirable feature of charging with LN_2-cooled ice is that it may be difficult to utilize it as a heat sink due to the problem of heat transfer to a solid (but fusible) mass. There are several ways to overcome this problem and a few are outlined below: all need a careful engineering appraisal to indicate whether the weight saving in expendable fluid is negated by the increase complexity, mass, and volume of the unit.

(1) Employ an ice-storage vessel with an internal-finned heat exchanger carrying a low-freezing-point circulating fluid such as silicone oil. At liquid nitrogen temperatures, silicone oil has a negligible vapor pressure and could be used to cool the suit water in a separate heat exchanger. It could also be

used as the primary coolant liquid in the LCG. This same fluid could be used with an external heat exchanger located in the spacecraft to cool the water originally to -320°F with liquid nitrogen.

(2) Use an ice-silicone oil slurry in the storage vessel and circulate the silicone oil as before. In this system, no internal heat exchanger is necessary. Use of an ice-silicone oil slurry has an additional advantage if expendable fluid systems were not used. Through the use of shadow-shielding of storage containers from solar and/or lunar shine, it may be possible to cool passively the material by radiant exchange with outer space and thereby prepare the system for operation without additional use of power or expendable materials. If there is a short mission, through suitable control of the rate of ice melting within the slurry, it may be possible to utilize only the heat of fusion of the material and not have to evaporate the water to space. Thus, a saving in material can be achieved for short-duration missions.

(3) Use a subcooled block of ice which is allowed to sublime to space and which has built-in passages for coolant flow. At -320°F, the rate of sublimation of ice to space is negligible so no sublimation would occur until a higher temperature was attained. Such a device would be difficult to build as a lightweight unit since all the water must be stored originally as ice. One would like to find an expendable fluid that is better than water. Many have been studied, including subliming salts (10), however, water is still best when ease of handling and safety

are considered, when heats of vaporization are examined, and when other thermal and physical properties are evaluated. Although most of the thermodynamic principles were discussed with a general fluid in mind, it is now apparent that the smallest volume and lightest mass expendable cooling systems will employ water.

Example of a Novel, Expendable Fluid, Life Support System

To illustrate some of the ideas presented earlier, and to stimulate imagination, a novel life support system is shown in Figure 9. Metabolic heat is removed by a liquid cooled garmet (LCG). The coolant water is circulated to and from a water reservoir that is vented to space. The temperature of the water to the LCG is determined by the pressure in the reservoir. The pressure, in turn, is determined by a pressure-control valve which is set by the astronaut. The returning fluid drives a turbine and vane assembly to separate the flashed water vapor from the liquid. Thus the device will operate satisfactorily in a zero-g environment.

If the water is only circulated through the LCG and a 10°F temperature rise is allowed, then the flow rate is about 0.4 gpm for a metabolic heat load of 2000 Btu/hr.

The device is extremely simple light weight, the mass consisting almost entirely of the expendable water, pump, and vent valve.

Also shown in Figure 9 is another variation from the normal life support system concept. Rather than use a gas circulation blower and chemical removal of the CO_2, water flow from the reservoir is first passed through a jet momentum pump wherin gas is drawn from the suit and contacted with the cold water. Downstream, the gas and liquid are separated in a small rotary, conical unit. The liquid then flows to the LCG and the gas is circulated back to the helmet. By this technique, the suit gas is dehumidified to a level equivalent to the saturation pressure of the circulating water. CO_2 is removed by dissolution in the water (to be flashed off after the water flows back to the low-pressure water reservoir). Most trace contaminants would also be removed. To increase the removal of metabolic CO_2, due to the low solubility of CO_2 in water, a high liquid flow rate is necessary. However, a dilute solution of $Cs_2CO_3 \cdot CsHCO_3$ with or without arsenite catalyst may be used in the reservoir to increase the CO_2 capacity of the flowing water. Such an inert salt solution should not interfere with the operation of the reservoir or cooling of the suit.

Other modifications of the concept are possible, but the general idea is clear. The principal motivation for suggesting such a system is to encourage new ideas in the development of light weight, reliable portable life support systems.

Non-Expendable Refrigeration Systems

The two most common non-expendable refrigeration systems are the vapor compression refrigeration cycle and the absorption refrigeration cycle.

In all refrigeration systems, it is imperative to minimize the work required for two reasons. First, the work input is eventually degraded to thermal energy which increases the heat load requirement and second, the work input will presumably be supplied by batteries which, in themselves, add considerable mass to all the over-all system. A measure of the required work can be estimated from the coefficient of performance (COP), i.e., the Btu of refrigeration per Btu of work input. For example, if a refrigeration system had a COP of two, then for every Btu of heat removed from the astronaut, one-half of a Btu of work must be used and 1.5 Btu of heat dissipated to the environment.

For a metabolic rate of 2000 Btu/hr, it is obvious that high COP values are essential to keep the power requirements within reason. Table 3 indicates these values.

Table 3

Relationship between COP and Work for a Refrigeration Load of 2000 Btu/hr

COP	Work Required (watts)	Total Heat Rejected to Space (Btu/hr)
1	580	4000
2	290	3000
5	116	2400
10	58	2200
20	29	2100

The "ideal" COP or maximum value depends upon the temperature to which the working fluid is raised to radiate the heat to space. This ideal COP is given as:

$$\text{ideal COP} = \frac{530}{T - 530}$$

The value of 530°R is the approximate temperature at which metabolic heat flows from the body to the working fluid and T is the temperature attained by the working fluid flowing to the radiator.

Table 4

Relationship between COP, Radiator Temperature and Power for Q = 2000 Btu/hr (Metabolic).

T, °F	T, °R	Maximum COP	Minimum Power, watts
140	600	7.6	76
212	672	3.7	160
400	860	1.6	360

It is readily seen from Table 4 that high values of radiator temperature are associated with low values of COP and large power requirements. High values of radiator temperature are, however, necessary if reasonable sized radiators are to be used. If we choose as a standard a radiator at 530°R to dissipate a certain Q and let it be A ft^2 in area (calculations show A $\sim$ 25 ft^2 for 2000 Btu/hr) then for the values of the radiator temperature shown above, taking into account the additional heat load from the refrigerating device, new area values are shown in Table 5.

Table 5

Radiator Areas for Different Radiator Temperatures

T, °F	Area of Radiator, arbitrary units
70	A
140	0.77A
212	0.51A
400	0.23A

There is obviously a very delicate trade-off between power, reflector size, and the radiator temperature. These calculations were made for ideal cycles; in a realistic analysis, irreversible effects will have to be considered.

Absorption refrigeration systems are too complex, have a low COP and are not feasible for portable life support systems. Compression refrigeration units are possible, but as indicated above, a choice would require a detailed weight and power optimization. For short term astronaut missions, it does not appear that either these refrigeration systems or others of the thermoelectric type are suitable.

Summary

Many concepts, new and old, which may be applicable for use in portable astronaut life support systems have been discussed. It now appears that a workable, light-weight system is possible. It is concluded that oxygen is best supplied from very high pressure storage tanks, CO_2 removed with LiOH or by membrane permeation and metabolic heat by water evaporation. However, optimum specific techniques to accomplish these steps are not at all clear. The research and engineering of portable life support systems is not yet complete!

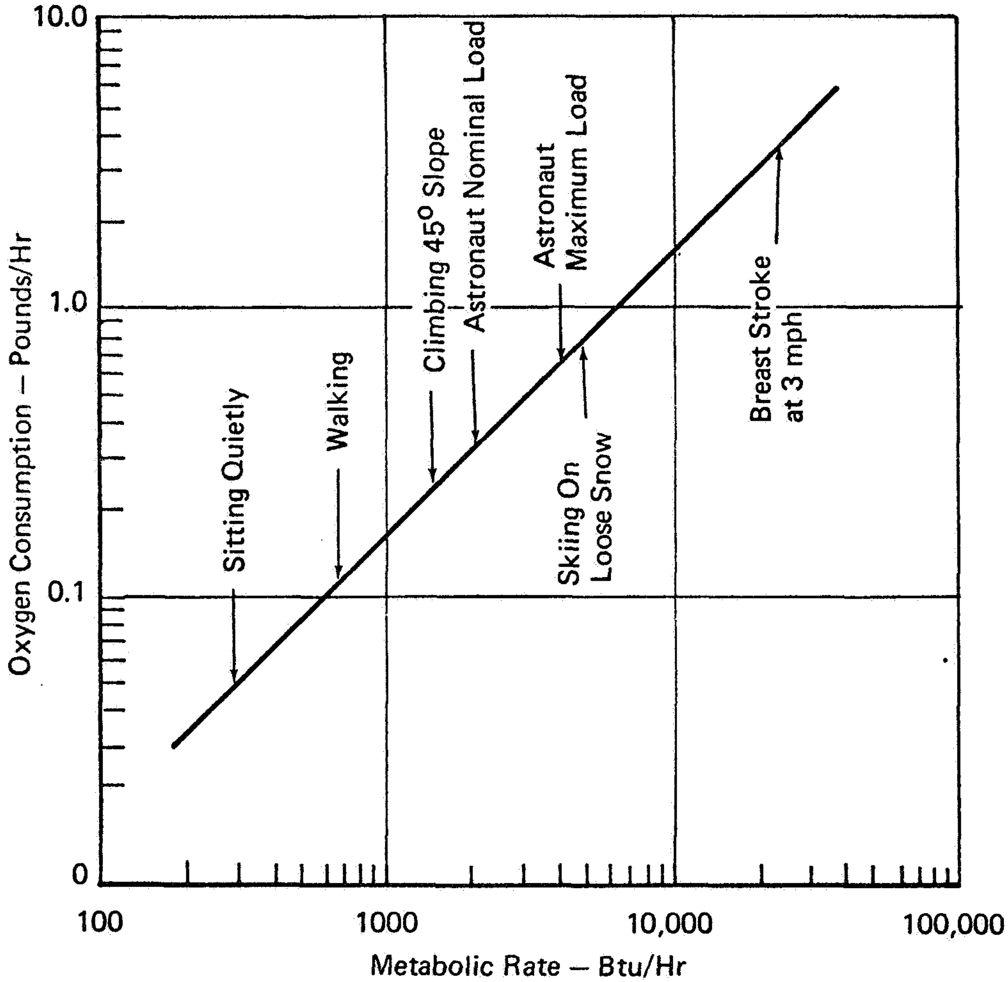

FIGURE 1 OXYGEN CONSUMPTION RATES FOR DIFFERENT METABOLIC LOADS

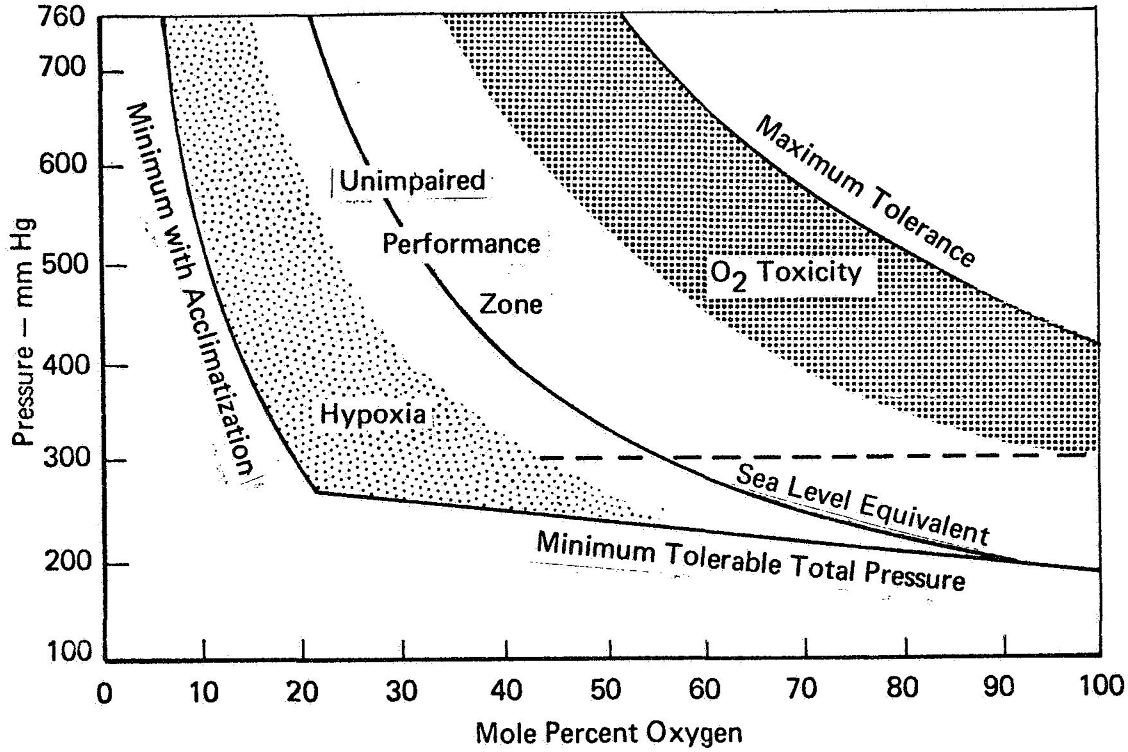

FIGURE 2a EFFECT OF OXYGEN ON HUMANS (4)

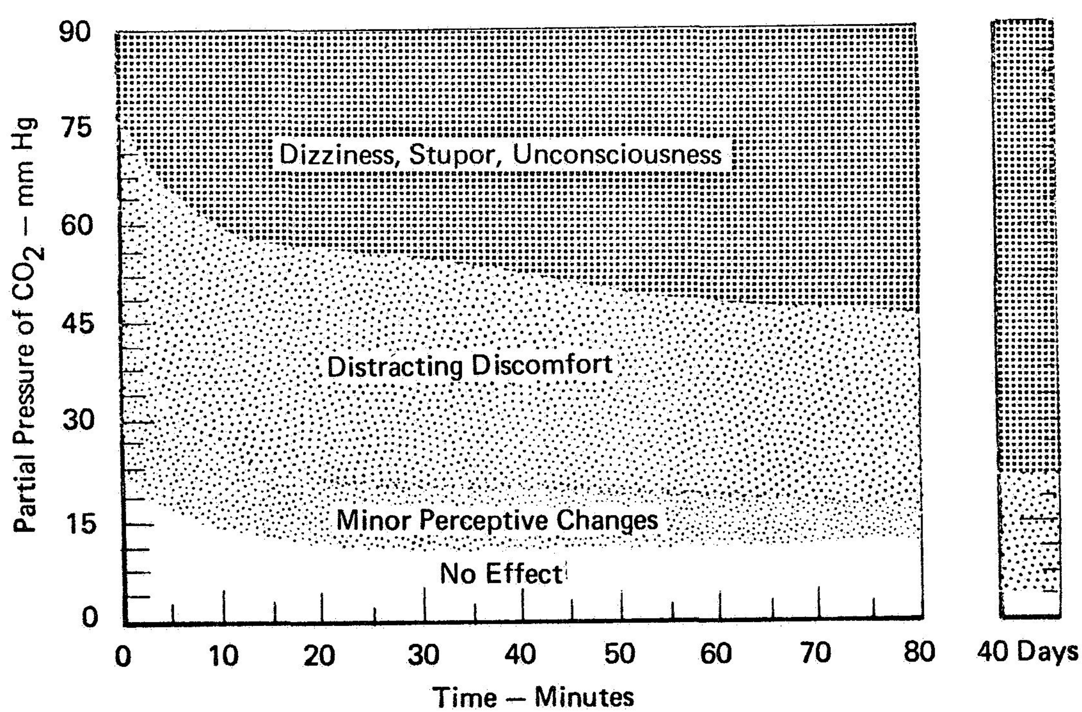

FIGURE 2b CARBON DIOXIDE EFFECTS ON HUMANS (4)

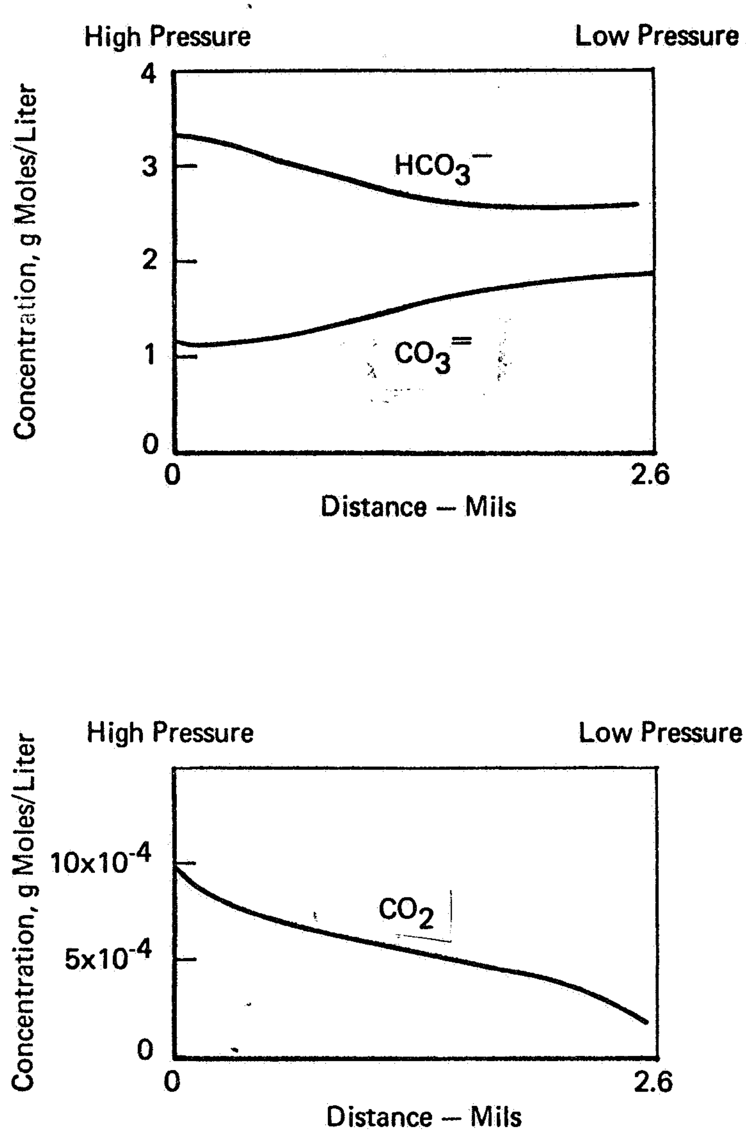

FIGURE 3 **CONCENTRATION PROFILES IN Cs_2CO_3 – $CsHCO_3$ LIQUID FILM (31)**

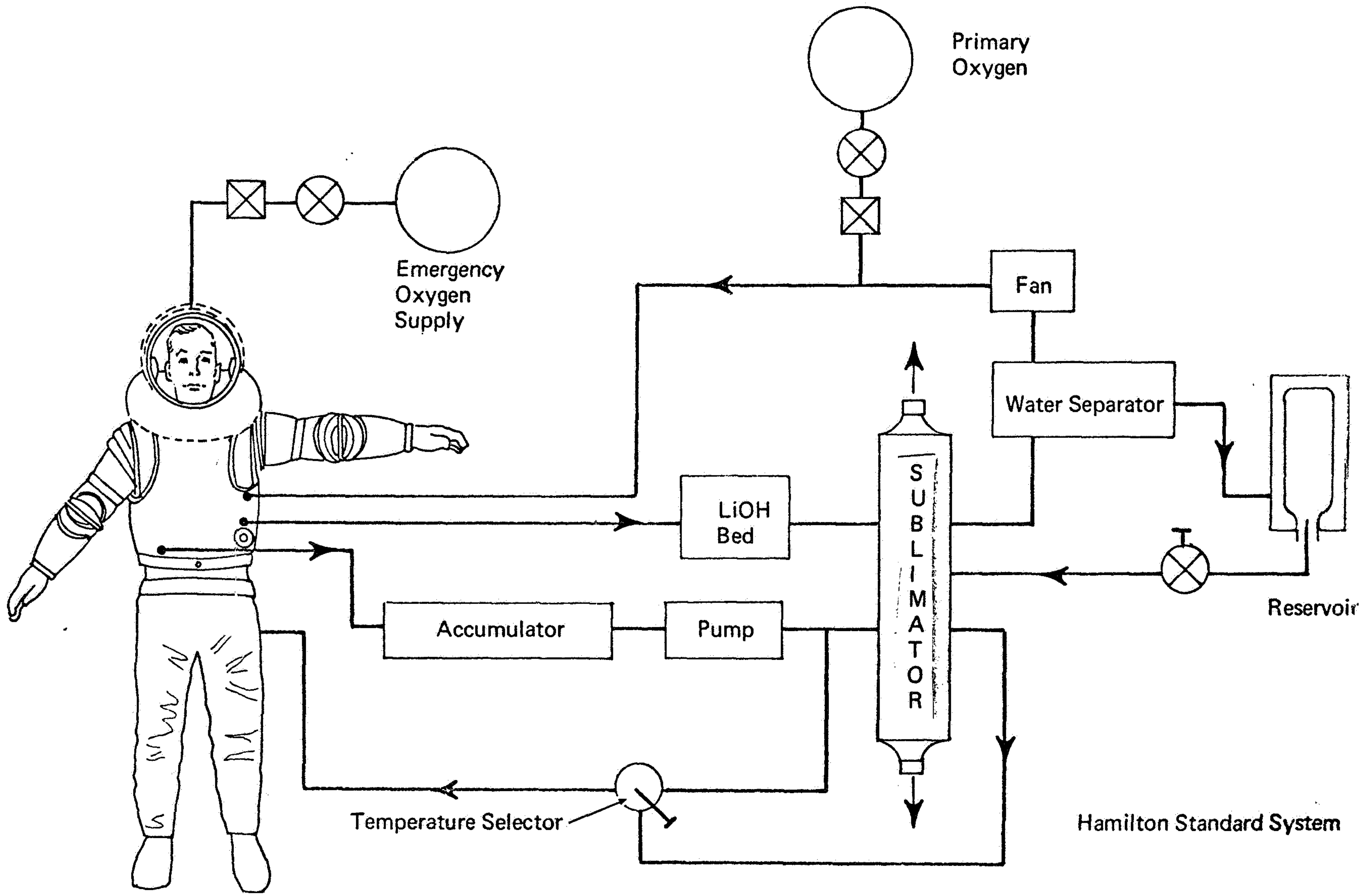

FIGURE 4 SPACE SUIT ENVIRONMENTAL CONTROL SYSTEM

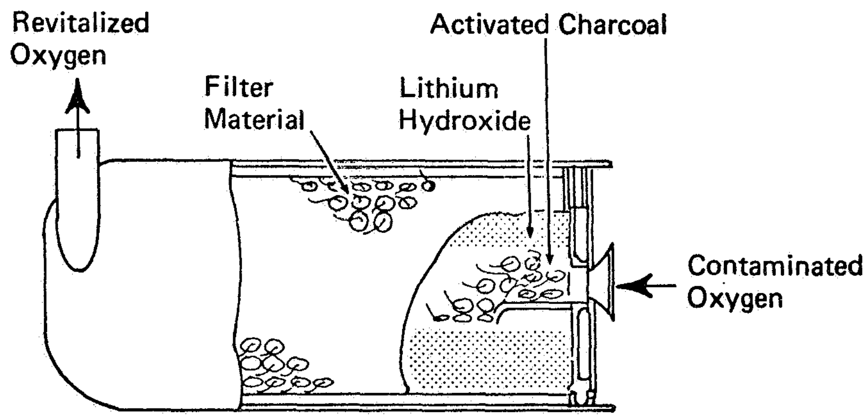

FIGURE 5 CONTAMINANT CONTROL CANISTER

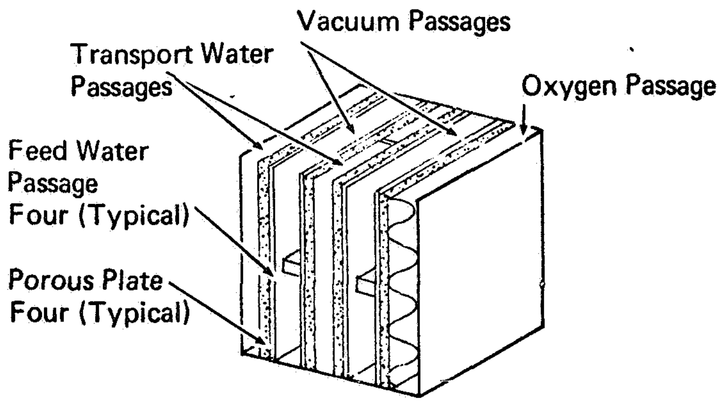

FIGURE 6 POROUS PLATE SUBLIMATOR

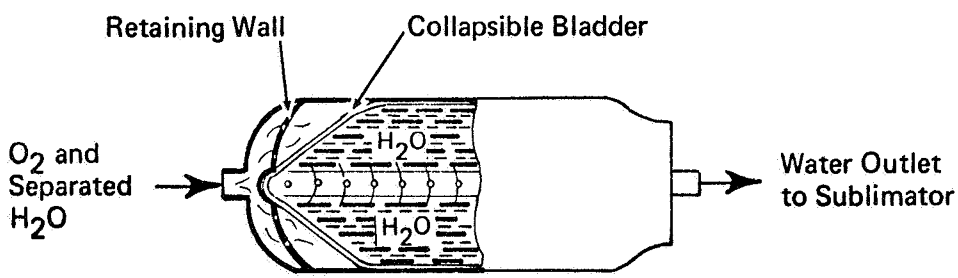

FIGURE 7 FEEDWATER RESERVOIR AND ACTIVE BLADDER EXPULSION SYSTEM

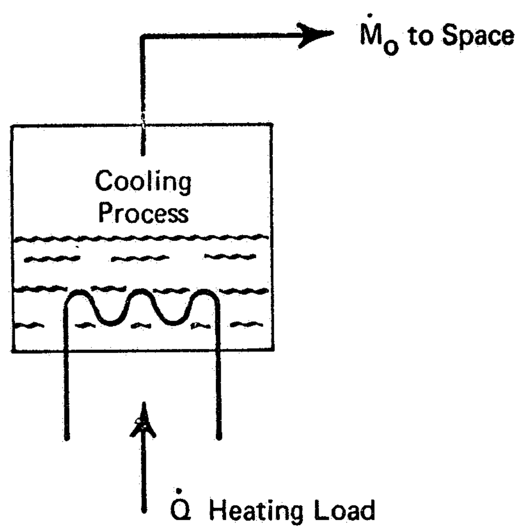

FIGURE 8 SCHEMATIC OF COOLING PROCESS

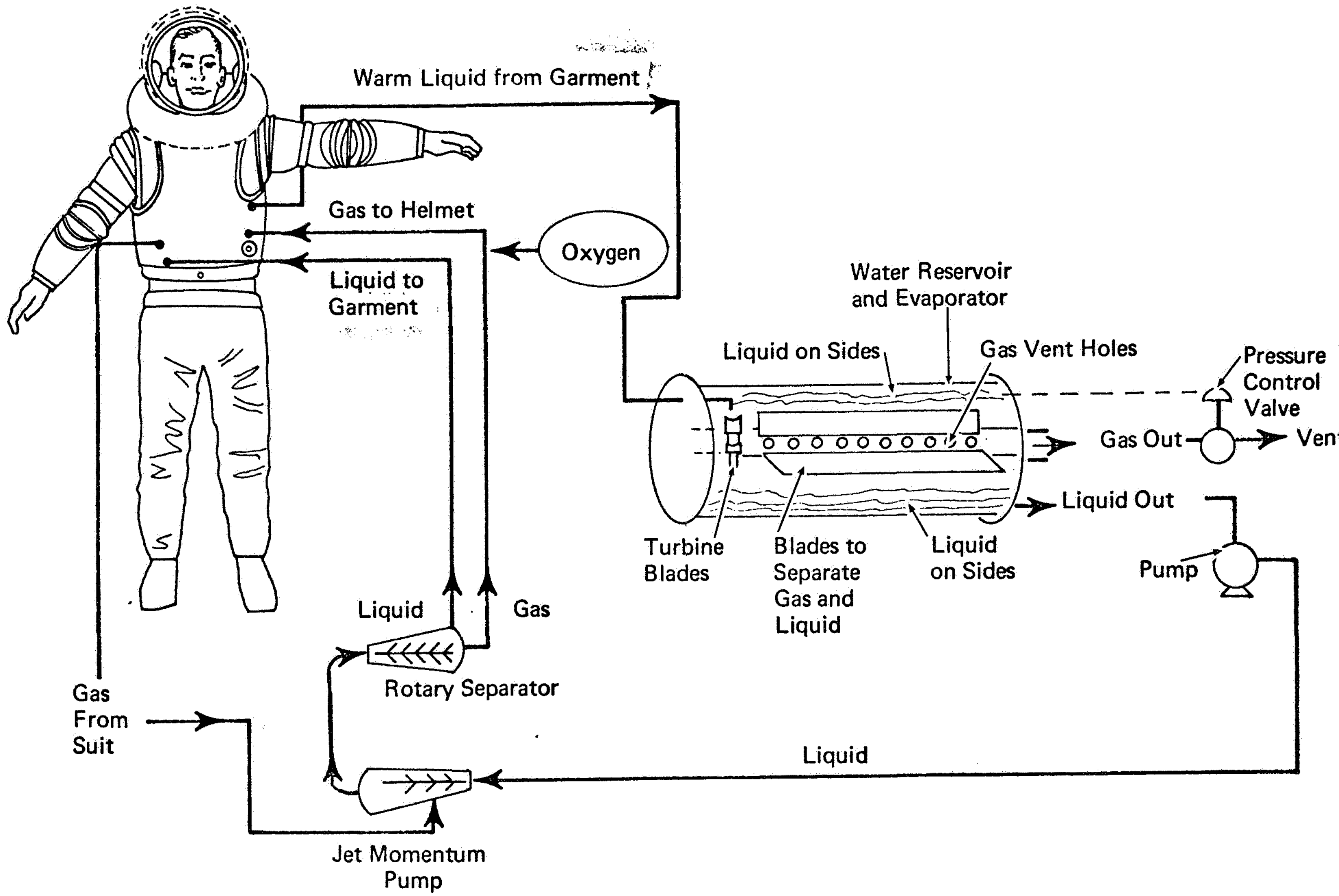

FIGURE 9 SCHEMATIC OF A THERMAL CONTROL SYSTEM WITH A TEMPERATURE-CONTROLLED RESERVOIR

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